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14. ABSTRACT

Work was initiated to systematically investigate the physical properties of the newly identified quantum phases of two-dimensional (2D) electrons in extremely high mobility GaAs/AlxGa1-xAs heterostructures, using microwave spectroscopy, in low temperatures and at high magnetic fields.

We have completed four experiments investigating: (1) melting of the 2D electron crystalline solid, (2) pinning of the bilayer crystals with pseudospin, (3) pinning of the electron liquid crystal, and (4) the skyrmion crystal to Wigner crystal cross-over. In addition we have successfully constructed a mechanical rotator to tilt the 2D electron sample which is mounted in the 10GHz microwave probe at 35 mK in a 45T magnet. This rotator is made available to all experimenters using the User Facility of the National High Magnetic Field Laboratory in Tallahassee, Florida.

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EXPERIMENTS ON NOVEL PHASES OF 2D ELECTRONS IN ADVANCED SEMICONDUCTOR STRUCTURES

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INTRODUCTION

Work was initiated to systematically investigate the physical properties of the newly identified quantum phases of two-dimensional (2D) electrons in extremely high mobility $GaAs/Al_xGa_{1-x}As$ heterostructures, using microwave spectroscopy, in low temperatures and at high magnetic fields.

We have to date completed four experiments investigating: (1) melting of the 2D electron crystalline solid, (2) pinning of the bilayer crystals with pseudospin, (3) pinning of the electron liquid crystal, and (4) the skyrmion crystal to Wigner crystal cross-over. In addition we have successfully constructed a mechanical rotator to tilt the 2D electron sample which is mounted in the 10GHz microwave probe at 35 mK in a 45T magnet. This rotator is made available to all experimenters using the User Facility of the National High Magnetic Field Laboratory in Tallahassee, Florida.

In this final report, I briefly describe these accomplishments and refer the interested readers to the journal publications at the end of the report.

WORK ACCOMPLISHED

(1) Melting of Quantum Solids of Two Dimensional Electrons in High Magnetic Field: Effects of Many-Body Correlation and Disorder

When a magnetic field (which is applied perpendicularly to a high quality two dimensional electron system) becomes sufficiently strong, the fractional quantum Hall liquid states will transition into an insulating phase of disorder-pinned electron solid. Controversy exists regarding the exact nature of this solid, as to whether it is essentially a classical solid (the expected state in the limit of infinite B), or a quantum solid, where many-body correlation can still be important. In this work we discover experimental evidence that unambiguously suggest the quantum nature of the solid, from systematically studying its melting behavior in multiple samples using microwave spectroscopy. We found that the electron solid melting temperature (Tc) in each sample is controlled only by the Landau level filling factor $\nu = nh/eB$ (n being the 2DES density), and not by n or B independently. At any fixed ν, T_c is insensitive to n ---- in stark contrast to a classical electron solid, whose Tc is determined by n (or Coulomb energy). This unique melting behavior, where T_c is controlled by inter-particle quantum correlation instead of the density, has not been previously observed for a solid and reflects the importance of many-body correlation in our system. We have also found that the (sample specific) pinning disorder enhances, not suppresses, T_c of the electron solid. In the lowest-disorder samples, we have found at least two distinct solid phases in high B (with a transition between the two controlled by ν), and the (T_c, ν) melting curve clearly demonstrates the ground state competition between quantum electron solids and FQH liquids.

(2) Pinning of bilayer Wigner crystals with pseudospin magnetism

We have studied the high-B Wigner crystal (WC) in bilayer hole systems, focusing on samples that show the bilayer exciton condensate (BEC) quantum Hall state at $\nu = 1$. We found pinning mode frequencies in such samples to be systematically enhanced from what would be expected from two classically interacting single-layer WC. The enhanced pinning deceases with increasing layer separation (d) and disappears for samples that do not show the $\nu = 1$ state. We suggest that interlayer quantum correlation and long range in-plane phase coherence similar to that in the $\nu = 1$ BEC state can also be relevant the bilayer WC (BWC) in high-B, and that our results give evidence for a pseudospin (layer index) ferromagnetic BWC, where carriers lose their individual layer identities and can experience enhanced pinning due to the interlayer spatial correlation of the disorder.

(3) Pinning of the electron liquid crystal phases

In ultrahigh mobility two-dimensional electron systems in the quantum Hall regime, the DC transport becomes strikingly anisotropic below 100 mK near Landau level filling factors $\nu = 9/2$, 11/2, 13/2, and so on. These states are known as the stripe or the liquid crystal phases of the 2D electrons.

We have studied the microwave (mw) conductivity spectra of these liquid phases in tilted magnetic fields. At zero in-plane field, the phase displays a pinning mode resonance when the mw electric field is perpendicular to the nominal stripe orientation, but not when the mw field is parallel. Application of in-plane magnetic field always causes the resonant and non-resonant directions to switch. During the switching, resonances of different frequencies can be present for the mw field along both directions. The measured pinning energy of stripes is found to increase significantly with the in-plane field. The pinning energy favors stripes parallel to the in-plane field, and therefore counteracts with the Hartree-Fock anisotropy energy calculated previously in aligning the stripes.

(4) Evidence of a Skyrmion Crystal to Single-Particle Wigner Crystal Crossover in their Pinning Mode Resonances

In a two dimensional electron system in magnetic field, the integer quantum Hall effect has its root in the discretization of the kinetic energy into a set of Landau levels. Each Landau level is further Zeeman-split into two spin-resolved branches. Even in the limit of zero Zeeman energy, the ground state with one branch completely filled and the other empty is a spin polarized itinerant ferromagnetic state. This is because the alignment of spins (and thus a symmetric spin wavefunction) lowers the exchange energy. The elementary excitation at LL filling factor $\nu = 1$ is not a single spin flip, but larger-scale smoothly distorting spin texture, known as a skyrmion by analogy with the Skyrme model used in nuclear physics. This object has a quantized charge *e*.

We have studied the pinning mode resonances of the crystal phases formed in the partly filled Landau level just away from integer fillings, $\nu = 1$ and $\nu = 2$, in the presence of an in-plane magnetic field. As an in-plane field is applied, the peak frequencies of the resonances near $\nu = 1$ increase, while the higher lying peak frequencies below $\nu = 2$ show no dependence on the in-plane field, and the difference between them decreases. This observation supports the interpretation of a skyrmion crystal phase being formed around $\nu = 1$ and a single-hole Wigner crystal phase below $\nu = 2$. The in-plane field causes shrinking of the skyrmion size and the crystal crosses-over to Wigner crystal with single spin flips.

(5) **Successful Construction of a Mechanical Rotator to Tilt the 2D Electron Sample Mounted in our 10 GHz Microwave Probe at 35mk in 45T Magnetic Field**

Because the usual coax cannot be bent, we used homemade flexible transmission lines, and clamped them to the long coax that goes to the top of the He^3/He^4 dilution fridge. The sample can be tilted with tilt angle up to 90° to allow parallel field application to change the electron Zeeman energy at fixed Landau orbital energy.

Journal Publications

(1) “Melting of a 2D quantum electron solid in high magnetic field”, Yong P. Chen, G Sambandamurthy, ZH Wang, RW Lewis, LW Engel, DC Tsui , LN Pfeiffer and KW West, Nature Physics Vol 2, 452 (2006).

(2) “Pinning modes and interlayer correlation in High-Magnetic-Field Bilayer Wigner Solids,” Zhihai Wang, Yong P Chen, LW Engel, DC Tsui, E Tutuc, and M. Shayegan, Phys. Rev. Lett. 99, 136804 (2007).

(3) “Observation of pinning mode of stripe phases of 2D systems in high Landau levels,” G. Sambandamurthy, RW Lewis, Han Zhu, YP Chen, Lloyd Engel, DC Tsui, LN Pfeiffer and KW West, (To be published in Phys. Rev. Lett.).

(4) “Pinning mode resonance of the 2D electron liquid crystal in an in-plane magnetic field”, Han Zhu, G. Sambandamurthy, LW Engel, DC Tsui, LN Pfeiffer, and KW West (in preparation).

PhD Thesis

“Microwave conductivity of Magnetic Field induced insulating phase of bilayer hole systems”, Zhihai Wang, Princeton University (June, 2007).